VOLUME 79 SEPARATE No. 231

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

AUGUST, 1953

AN ANALYSIS OF WATER QUALITY CRITERIS

by J. E. McKee and Vinton W. Bacon

SANITARY ENGINEERING DIVISION
(Discussion open until December 1, 1953)

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

THIS PAPER

--represents an effort of the Society to deliver technical data direct from the author to the reader with the greatest possible speed. To this end, it has had none of the usual editing required in more formal publication procedures.

Readers are invited to submit discussion applying to current papers. For this paper the final closing dead line appears on the front cover.

Those who are planning papers or discussions for "Proceedings" will expedite Division and Committee action measurably by first studying the printed directions for the preparation of ASCE technical papers. For free copies of these directions—describing style, content, and format—address the Manager, Technical Publications, ASCE.

This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

AN ANALYSIS OF WATER QUALITY CRITERIA

J. E. McKee[1], M. ASCE and
Vinton W. Bacon[2], Assoc. M. ASCE

SYNOPSIS

In an effort to formalize, standardize, and simplify the administration of water-pollution-control programs, several state and interstate agencies in the U. S. have developed fixed water-quality standards in conjunction with systems of stream classification or zoning. A few other such agencies rely upon effluent standards. In contrast, the philosophy of the new California water-pollution-control program rules out the use of rigid standards, relying instead upon the concept of case-by-case determination of whether pollution exists or threatens in each area and upon local regional administration of control. To assist the state and regional boards in their studies of individual problems of pollution, the State Board has sponsored and published a report prepared at the California Institute of Technology, entitled "Water Quality Criteria". This compendium represents a literature survey of the entire subject of water-quality criteria and it serves as a reference work for the limiting and threshold concentrations of potential pollutants for each major beneficial use of water.

Introduction

The concentration of population in urban areas, coupled with a greatly increased industrialization since the turn of the century, has multiplied the problems of water pollution and intensified the efforts of federal, state, regional, and local authorities to abate or diminish such pollution. These efforts have been manifested in a myriad of laws and methods of control varying from reliance upon the common law and the laws of equity, as in the State of Georgia, to a specific law based on an intricate system of stream classification and water-quality standards, as in the State of New York. With a view toward assisting states in establishing adequate legislation, the U. S. Public Health Service has prepared a Suggested State Water Pollution Control Act. Most of the state and interstate agencies involved in the control of water pollution, however, have formulated independent legislation to meet the specific needs and objectives of the local area.

It is the intent of this paper to review and analyze one aspect only of water-pollution control, namely the application and use of water-quality standards, classifications, objectives, or criteria. The paper deals with the various types of standards and their significance, the factors that militate against the use of rigid standards, the philosophy of the case-by-case meth-

---

1. Associate Professor of Sanitary Engineering, California Inst. of Technology, Pasadena, California.
2. Executive Officer, Calif. State Water Pollution Control Board, Sacramento, California.

od of pollution abatement, the need for a compendium of water-quality criteria, and how this need is being met.

No attempt is made herein to consider the legislation by which water-pollution-control boards or commissions are established, nor to consider the powers and duties delegated to such bodies, other than authorization or directives to establish standards and systems of stream classification. Furthermore, this paper does not cover the action of boards in requiring permits, approving plans, or operation of the program; nor does it concern itself with enforcement, penalties, or appeals from decisions of the boards. Although interesting and important to administrative personnel, such matters are beyond the scope of this analysis of water-quality criteria.

Definitions

Before continuing with this discussion, it is well to define several terms that occur frequently in this paper and similar articles dealing with water pollution. First, distinctions should be made among the words "standard", "objective", and "criterion".

The term "standard" applies to any definite rule, principle, or measure established by authority. The fact that it has been established by authority makes a standard somewhat rigid, official, or quasi-legal; but this fact does not necessarily mean that the standard is fair, equitable, or based on sound scientific knowledge, for it may have been established somewhat arbitrarily on the basis of inadequate technical data tempered by a cautious factor of safety. Where health is involved and where scientific data are sparse, such arbitrary standards may be justified.

The word "objective" represents an aim or a goal toward which to strive and it may designate an ideal condition. Most certainly, however, it does not imply strict adherence nor rigid enforcement by an agency or favor among engineers on boards and commissions that strive to achieve water-pollution control by persuasive methods and cooperative action.

A "criterion" designates a means by which anything is tried in forming a correct judgment respecting it. Unlike a standard it carries no connotation of authority other than that of fairness and equity; nor does it imply an ideal condition. When scientific data are being accumulated to serve as yardsticks of water quality, without regard for legal authority, the term "criterion" is most applicable. As such, it is used extensively in this paper.

Definitions are also indicated to distinguish among the words "contamination", "pollution", "nuisance", and "degradation". Because these terms are often confused and because some of them may be used synonymously, many legislative enactments relating to water-pollution control define one or more of them explicitly. In California[3], for example, "contamination" is defined as "an impairment of the quality of the waters of the State by sewage or industrial waste to a degree which creates an actual hazard to public health through poisoning or through spread of disease". The term "pollution" is defined as "an impairment of the quality of the waters of the State by sewage or industrial waste to a degree which does not create an actual hazard to public health but which does adversely and unreasonably affect such waters for domestic, industrial, agricultural, navigational, recreational, or other beneficial use". "Nuisance" is defined as "damage to any community by odors or unsightliness resulting from unreasonable practices in disposal of

3. Division 7, Water Code, State of California (1949)

sewage or industrial waste". While not defined explicitly, "degradation" is frequently used to express a deterioration in water quality as a result of natural causes such as erosion and swamp drainage.

Types of Standards for Water Pollution Control

There are two basic types of standards that have been used for control of water pollution. One type dealing with the quality of the receiving water, whether stream, lake, river, estuary, open ocean, or ground water, is commonly designated as "stream standards". The other type, referring to the quality of the wastes to be discharged from a given plant, is called "effluent standards". Each type has its advantages and disadvantages, each type has its advocates and opponents, and each type is in common use today.

Stream standards may be divided into two distinct categories (a) dilution requirements and (b) standards of receiving-water quality. Largely outmoded now, dilution requirements were favored at the turn of the century as handy yardsticks and rules-of-thumb. They were proposed first in 1887 for the Chicago drainage canal, when Rudolf Hering recommended a dilution rate of 3.3 cfs per 1,000 persons sewered[4]. Later Hazen, Goodnough, Stearns, and others in New England proposed requirements varying from 2 to 10 cfs per 1,000 persons, depending on the characteristics of the receiving waters[5].

Considerations of dilution entered into the recommendations in the Eighth Report of the Royal Commission on Sewage Disposal. Although these recommendations were never legalized by Parliament, they are generally quoted in bills before parliamentary committees and in courts of law in Great Britain[6]. The Royal Commission recommended that a general standard and several special standards be established, the choice of which in each instance would depend on local circumstances. In order to comply with the general standard, an effluent had to contain not more than 30 ppm of suspended matter and not more than 20 ppm of 5-day,B.O.D., without reference to dilution. In specifying special standards, however, the Royal Commission considered dilution as the chief factor. Where dilution exceeded 150 to 1, the limitation on B.O.D. was omitted and the suspended solids content was allowed to be as high as 60 ppm. Where dilution exceeded 300 to 1, the standard for suspended solids was relaxed further to 150 ppm; and with dilution in excess of 500 to 1, all tests could be waived, provided of course that esthetic requirements with regard to screenings and floating solids were considered.

Standards of quality of the receiving water are based on threshold and limiting values for specific substances in the water, and depend on the beneficial uses to which the water may be put. Widely used now and favored by those who feel that some sort of formalized criteria are necessary, stream standards are frequently correlated with a rigid system of stream classification or zoning whereby separate standards are set for each stream or zone. The principal advantage of standards of stream quality over effluent standards lies in the fact that they take into account dilution and the assimilative capacity of the receiving water and consequently they lead generally to an economy of treatment works for pollution abatement. On the other hand, such standards are more difficult to formulate and define, and more difficult to

---

4. "Stream Sanitation" by Earle B. Phelps, John Wiley and Sons (1949)
5. "Standards of Stream Sanitation", by H. W. Streeter, Sewage Works Journal 21, 115 (1949)
6. "The Examination of Waters and Water Supplies", by E. W. Taylor, P. Blakiston's Son and Co. (1949)

administer than effluent standards. Where stream classification is mandatory and complicated, the program may become extremely cumbersome.

The second general type, effluent standards, may also be divided into two broad categories; those that restrict the strength and/or amount of substance that can be discharged, and those that specify the degree of treatment or percentage removal of a specific pollutant that must be accomplished by treatment or by changes in industrial processes. As an example of restrictions on the strength of wastes, the Interstate Commission on the Delaware River, (Incodel) specifies that effluents discharged into Zone 1 shall have a B.O.D. not greater than 50 ppm and into Zone 2 not greater than 100 ppm.

Pennsylvania has pioneered in effluent standards that specify the amount of pollutant that may be discharged by special industries and each process within such industries. This program is based on a percentage removal of pollutants from "normal" for each process, as established by representatives of industry. Consequently the effluent requirements favor good housekeeping and penalize the inefficient operator.

Standards that specify the degree of treatment are also typified by those of Incodel which require, in addition to the limitations of B.O.D. as specified above, that the B.O.D. reduction of wastes discharged into waters of Zones 1 and 2 shall be at least 85% and that wastes entering Zone 3 shall have a B.O.D. reduction of at least 50%.

Effluent standards have the advantages of simplicity and ease of administration, for they are well-defined and equitable among communities and industries. Their primary disadvantage lies in their uneconomical use in some cases of the assimilative powers of receiving waters.

The Use of Standards by State and Interstate Agencies

Only three states (Maryland, Oregon, and Pennsylvania) appear to have adopted state-wide effluent standards, although in New Jersey effluent standards have been promulgated for two zones of the Raritan River. The Interstate Sanitation Commission, the Interstate Commission on the Delaware River (Incodel), and the Ohio River Valley Water Sanitation Commission (Orsanco) have utilized some form of effluent standards while the International Joint Commission (Canada and the U.S.), having no direct enforcement power, has recommended certain effluent "objectives".

Seven states (Maine, Maryland, New Hampshire, New York, Oregon, South Carolina, and West Virginia) have adopted independent state-wide water-quality standards in conjunction with systems of stream classification, and four other states (Indiana, Mississippi, Tennessee, and Washington) have some form of state-wide standards without stream classification. Four of the five principal interstate water-pollution-control agencies have promulgated stream standards and classification for the entire area of control, while Orsanco has adopted stream standards for a few specific reaches of the Ohio River.

Although stream standards and/or effluent standards are part of the pollution-control program in several state and interstate agencies, it is significant to note that the majority of states have avoided the use of any type of rigid state-wide standards, preferring instead to make case-by-case studies of each problem of pollution based on the beneficial uses of the water involved and the general economy of the region being considered. Of the 48 states, 26 have no state-wide water-quality standards while 10 additional states have no such standards other than those resulting from interstate compacts. (Note:

The information in the three foregoing paragraphs was applicable as of January, 1952. Since then, action may have been taken by some agencies to establish, modify, or eliminate standards).

Factors That Militate Against Rigid Standards

Water-quality standards for streams or effluents provide the regulatory agencies with definite yardsticks established or authorized by legislation, thereby facilitating greatly the problem of administering a pollution-control program. On the other hand, this ease of administration may result in arbitrary decisions and possible inequities to municipalities and industries. These inequities arise from the fact that many variables other than the strength and volume of the substance in question influence the effect of pollution on the beneficial uses of water. Among these variables are included the effects of pH, temperature, synergism or antagonism, dilution, mixing, tidal action, chemical and biochemical changes, and hydrographic features, to mention only a few. The combination and interplay of these many factors are extremely complex and they exert such an influence on each pollution problem that the broad-brush application of state-wide standards for streams or effluents may prove to be inadvisable. A complete discussion of each of these factors is beyond the scope of this paper, but the following brief descriptions should serve to emphasize the significance of several variables in relation to three beneficial uses of water, viz., the propagation of fish and other aquatic life, irrigation, and industrial processes. Similar analyses could be made for other beneficial uses.

Propagation of Fish and Other Aquatic Life

The time-concentration relationship is very important in all studies of tolerances of aquatic life toward pollutants. Thus, an organism may withstand a 10-minute exposure to 200 ppm of a certain substance, followed by a return to clear water, without any apparent deleterious effect; yet the same organism may succumb to repeated 10-minute exposures of that concentration or to a continuous exposure of only 20 ppm of the same substance. On the other hand, by continuous exposure to gradually increasing concentrations, the organism may build up a tolerance to concentrations that would be toxic to a non-acclimated organism. The effects of long-term exposures of fish populations to very low sub-lethal concentrations are not clearly understood.

This relationship of concentration and time of exposure is extremely significant in considering the effect of a slug of waste on the aquatic life of a stream. Normally a slug would be more deleterious than a steady uniform discharge with adequate mixing, but in some instances the concentrated slug may be less detrimental than the steady weak pollution. Or, perhaps the lack of lateral or longitudinal mixing in a stream or tidal estuary may be advantageous if it produces a local concentration into which fish may swim accidentally, but from which they can escape to clear water in a few minutes without permanent injury.

The effects of harmful substances upon fish life vary with species, size, age, and physiological condition of the individuals. Water favorable for some species may not necessarily be adequate for others that have been adapted to somewhat different conditions.

These effects vary also with the physical and chemical composition of the water supply; for example, in soft water the damaging effects of poisons are generally greater than in hard water. In distilled water, very low concen-

trations of some pollutants are deleterious. Decreased oxygen concentrations and higher temperatures tend to increase the susceptibility of fish to toxicants[7].

Interrelationships among the dissolved constituents of the water supply are also extremely important. By synergistic action, the combined influence of several substances simultaneously may result in greater damage to fish life than the sum of the individual effects taken independently. For example, combination of sulfates of cadmium and zinc, or nickel and cobalt, are additive in effect, but combinations of sulfates of copper and zinc, copper and cadmium, or nickel and zinc can produce up to five times the reaction that would be expected if the effect were simply additive[8]. On the other hand, certain combinations of salts act antagonistically to reduce the injurious effects of each. For example, mixtures of salts have become progressively less toxic when to sodium chloride solution has been added calcium chloride, then potassium chloride, and finally magnesium chloride[9].

Hydrographical features of water courses and fluctuating water levels, particularly in impoundments, may also act to modify the effect of pollutants on fish in their natural habitats[10].

Owing to the many variable factors governing the effects of pollutants, coupled with the complexity of many effluents, chemical and physical data alone may be insufficient to predict the results of pollution upon the aquatic life of a body of water. While probable safe limits of concentrations of various materials can serve as a helpful guide for industry, it is generally a good policy to conduct supplemental biological tests, or bioassays, upon the organisms involved, or upon suitable indicator organisms. Recently, attention has been given increasingly to the development of practical standard methods of procedure for performing routine bioassays in or near the industrial plants whose effluents are potentially hazardous for fish[11].

Irrigation Water

Absolute limits to the permissible concentrations of pollutants and salts in irrigation waters cannot be fixed[12] for several reasons: (a) It is almost universally true that the soil solution is at least three to eight times as concentrated as the water that replenishes it, owing to the evaporation of water from the soil surface, transpiration of plants, and the selective absorption of salts by the plants. (b) There is apparently no definite relationship between the concentration and composition of the irrigation water and those of the soil solutions, which in some cases may be as much as 100 times more

---

7. "Temperature and Fishes", by M. M. Ellis, Fishery Leaflet 221, U.S. Fish and Wildlife Service (1947)
8. "Intensified Injurious Effects on Fish, Especially the Increased Toxic Effect Produced by a Combination of Sewage Poisons", by H. J. Bandt, Chem. Abst. 42, 9015 (1948)
9. "The Resistance of Fresh-water Fish to Changes of Osmotic and Chemical Conditions", by W. C. Garrey, Amer. Jour. Phys., 39, 313 (1916)
10. "Studies in Freshwater Fishery Biology", by K. F. Lagler, 3rd revised edition, J. W. Edwards, Inc., Ann Arbor, Mich. (1949)
11. "Biological Observations and Toxicity Bioassays in the Control of Industrial Waste Disposal", by Peter Doudoroff, Proc. 6th Indus. Waste Conf., Purdue Univ., Feb. 21-23 (1951)
12. "Permissible Composition and Concentration of Irrigation Water", by W. P. Kelley, Transactions, Am. Soc. C. E. 106, 849 (1941)

concentrated than the water. (c) Plants vary widely in their tolerances of salinity as well as their resistances to specific salt constituents. (d) Soil types, climatic conditions (such as temperature, rainfall, and humidity), and irrigation practices may all influence the reactions of the crop to the salt constituents. (e) Interrelationships between and among substances may be highly significant, i.e. the effect of one ion may be modified by the presence of another. Such antagonistic influences, for example, operate between calcium and sodium, boron and nitrates, or selenium and sulfates[13].

Good drainage of the soil may be a more important factor for crop growth than the salts in the irrigation supply. Even when excellent waters are used, poorly drained land may sometimes go out of production. Highly saline waters, on the other hand, may sometimes be used on open well-drained soils.

The concentration of salts in natural irrigation waters is rarely so high as to cause immediate injury to crops. If leaching of the root zone does not take place, however, the concentration of the soil solution at this depth will increase with successive irrigations until it reaches the limit of solubility of each salt. The solubility of many salts, such as borates, chlorides, and sulfates of sodium and magnesium, is beyond the tolerance limit of many plants; consequently, these salts can build up to toxic concentrations. The slow filling of the soil with salts, resulting in the production of highly concentrated soil solutions, eventually will force the abandonment of an irrigated area. This action may have been the cause of failure of many ancient irrigation systems.

In any discussion of the quality of water for irrigation, it is necessary to consider the effects of its constituents on both the plant and the soil. The deleterious effects of salts on plant growth can result from: (a) direct physical effects of salts in preventing water uptake by plants (osmotic effects); (b) direct chemical effects upon metabolic reactions of plants and/or (d) indirect effects through changes in soil structure, permeability, and aeration[14]. Owing to the many variable factors that influence the effects of pollutants and salts on crops and soil, it is apparent that rigid standards are not applicable to irrigation waters.

Industrial Process Water

There are hundreds, even thousands, of industrial processes that utilize water and for each process there is an optimum quality of water. Some processes require water bordering on the chemically pure; others can tolerate water containing moderate concentrations of pollutants; and a few need water of such high chemical content that salts must be added to achieve optimum results. Needless to say, it is impossible to organize the quality requirements of the waters used for each of the many different industrial processes into a single standard. Such quality requirements differ far too much to allow any broad generalization or simplification.

One characteristic, however, is of primary importance for all industries, namely that the concentrations of the various constituents of the water remain relatively constant. Once a process is started and the difficulties created by the presence of undesirable constituents are eliminated, the original poor quality of the water is probably not as important as having the quality remain

13. "The Salinity of Irrigation Water", by Carl S. Scofield, Smithsmian Report, 275 (1935)
14. "Irrigated Soils, Their Fertility and Management", D. W. Thorne and H. B. Peterson, P. Blakiston's Son and Co., (1949)

constant. Short-time variations in concentrations of substances in the process water require continued attention and added expense.

Although many studies have been made of the quality requirements of water for use in certain industries, there remain numerous other industries for which the requirements of water quality have not been specified in public documents except in a general and qualitative way. Perhaps the most thorough study of the water-quality requirements of various industries has been that conducted by the New England Water Works Association Committee on Water Quality Tolerances for Industrial Uses[15].

The foregoing paragraphs deal with the many variables that influence the effects of pollutants on three major uses of water, but the reader will recognize that the interplay of these many factors may also militate against rigid standards for other beneficial uses of water, such as for recreation, stock and wildlife watering, and even domestic supplies.

The California Concept of Pollution Control

Granted, then, that rigid standards and systems of stream classification or zoning are subject to many variable factors that might produce inequities and unpredictable effects, how can pollution control best be achieved with fairness and economy for the potential polluter as well as the beneficial user of water? One answer to this question lies in the philosophy of the new water-pollution-control program in California.

Established in 1949, this program provides a means for coordinating the pollution-abatement activities of the various state agencies and political subdivisions through a State Water Pollution Control Board and nine regional boards. Primary control is exercised on the regional level inasmuch as problems of water pollution in California are dependent upon factors of precipitation, topography, population, and the development of recreational, agricultural, and industrial assets, all of which may vary greatly from region to region. Insofar as problems of water pollution are involved, the snow-capped mountains of northern California differ from the Mojave desert as significantly as Vermont differs from Arizona; and the industrialized San Francisco bay area is as different from the San Joaquin valley as New York harbor is from central Texas.

The California Water Pollution Act of 1949 was designed to provide the means for establishing an equitable and economic balance among the many beneficial uses of water by application of the principle of case-by-case determination as to whether or not a condition of pollution threatens or exists. Departing sharply from practice in many states that utilize stream or effluent standards, this principle provides that each pollution problem be analyzed individually to determine its effect upon present and future beneficial uses of the water in accordance with long-range plans and policies which, by statute, must be formulated by the boards. Furthermore, these plans and policies will in all cases be tied into the State Water Plan as adopted by the California Legislature.

Of necessity, the case-by-case stipulation precludes a broad-brush treatment on a state-wide or even regional basis, and it rules out rigid stream standards and the arbitrary zoning of streams or underground basins. In

15. Progress Report of Committee on Quality Tolerances of Water for Industrial Uses, Jour. New Eng. Water Works Assn. 54, 261 (1940)

effect, it depends on astute judgment by members of the water-pollution-control boards and such judgment must be founded on the most recent, complete, and reliable compendium of data pertaining to the limiting and threshold concentration of each potential polluting substance, for each possible beneficial use of the water.

Recognizing the need for such a compendium upon which individual water-quality objectives or requirements could be based, the State WPC Board entered into an agreement with the California Institute of Technology on 4 January 1951 to make a literature survey dealing with water-quality criteria for various beneficial uses of water, and to submit a final report of its survey. It was the primary aim of this project to assemble, condense, and evaluate the readily available literature pertaining to water quality and its effects upon the beneficial uses of water. Such literature included the fundamental work of original investigators as well as standards and requirements of other state and interstate agencies. The scope of the survey included, furthermore, a review of judicial expressions to determine court rulings and decisions that have dealt with the reasonableness or unreasonableness of water-quality standards as established by public agencies. The second aim of the project was to present the material in a manner that would be most useful to the water-pollution-control boards and their staffs, i.e., to design the report to serve as a manual or handy reference for water-quality criteria.

Following chapters of introductory material and general considerations, the results of the literature search are presented under four main headings. The first is a compilation of water-quality criteria as promulgated by state and interstate control agencies in the United States. The second is a review of judicial expressions dealing with water-quality criteria, i.e., instances of water-pollution litigation in which the courts have mentioned the validity, reasonableness, or applicability of technical data and standards. The third heading lists the quality objectives for major beneficial uses of water, in as much detail as the reference material allows, including many sub-headings for each category.

The fourth heading, constituting the major portion of the work, is a listing of all potential pollutants on which data are readily available. This chapter is arranged alphabetically by the correct or most common names of physical, inorganic, organic, biological, or radioactive substances, and extends from "abietic acid" to "zinc sulfate." Where substantial data are available, each discussion is listed under four sub-headings: General, Cross References, Bibliography, and Effects on Beneficial Uses. This listing, especially, spotlights the need for additional research to fill the numerous gaps in the present knowledge of water-quality criteria.

Recognizing the fact that new information on water-quality criteria is being published each month and that some significant references may have been overlooked in the original survey, the California State Water Pollution Control Board is planning to bring the report up to date periodically. Provision has already been made to continue the literature survey during 1953 and 1954 to cover material published in the two years since the original report was written.

Conclusion

Utilizing a new and unique approach, California has decentralized its program of pollution control into nine regions, each with its own board which coordinates all pollution abatement measures of all agencies. In lieu of state-

wide or even region-wide water-quality standards for streams, ground-water, or effluents, and in lieu of a system of zoning or classification, the new legislation in California relies on a case-by-case study of each problem of existing or potential pollution. To assist the state and regional boards in such studies, a compendium of water-quality criteria has been published by the State Board. As a manual or handy reference work, this volume, "Water Quality Criteria", should prove useful to all engineers and scientists engaged in pollution control.